Sensitivity analysis on the levelized cost of energy for floating offshore wind farms

Markus Lerch[a*], Mikel de Prada Gil[a], Climent Molins Borrell[b], Gabriela Benveniste[a]

[a] *IREC Catalonia Institute for Energy Research, Jardins de les Dones de Negre 1, 2a., 08930 Sant Adrià de Besòs, Barcelona, Spain*

[b] *UPC Universitat Politècnica de Catalunya, Department of Civil and Environmental Engineering, Calle Jordi Girona 1-3, 08034 Barcelona, Spain*

Abstract

In this paper, a sensitivity analysis is performed on the levelized cost of energy (LCOE) for floating offshore wind farms (FOWFs). The analysis is carried out for three floating wind turbine concepts and three different offshore sites. At first, a methodology is presented for calculating the LCOE for a specific FOWF. Afterwards, the base LCOE values for each of the floating wind turbine concepts and sites are obtained. The sensitivity analysis includes over 325 input parameters that are studied in order to identify the ones that most influence the LCOE. Furthermore, a complementary sensitivity analysis is performed by varying the input parameters based on uncertainty ranges provided by each of the concept designers. This serves to obtain maximum and minimum LCOE variation limits and possible cost reduction potentials. It has been observed that the capital cost related parameters such as turbine, substructure and mooring system manufacturing cost as well as power cable cost are some of the most influencing parameters besides common parameters such as the discount rate and energy losses. The LCOE variation limits obtained in this study vary between 67€/MWh and 135€/MWh among the different concepts and offshore sites including offshore transmission costs.

Keywords: Floating offshore wind farm, sensitivity analysis, life cycle costs, levelized cost of energy

---

*E-mail address: mlerch@irec.cat Tel.: +34 933562615 Fax.: +34 933563802
Corresponding author (Markus Lerch)

1. Introduction

The offshore wind sector has reached a global installed capacity of more than 18.8GW at the end of 2017, of which nearly 84% is located in European waters. The majority of offshore wind farms in Europe are placed in the shallow waters of the North Sea (71%), Irish Sea (16%) and the Baltic Sea (12%) at an average water depth of 27.5m [1]. Considering the abundant wind resources available offshore, the industry has the potential to continue to grow. However, the current technology based on bottom-fixed offshore wind turbines faces technical and economic limitations with increasing water depths [2]. Since shallow waters are scarce around the world, it becomes necessary to develop technical solutions to unlock the abundant wind resources of deep water areas [3]. Floating substructures for offshore wind turbines are a promising solution that has been under development in recent years. They possess lower constraints to water depths and soil conditions and can be applied from shallow to deep waters, thus allowing to take advantage of the full potential of offshore wind [2].

Several countries such as Portugal, Scotland and France have recognized this potential and have installed prototypes offshore. In addition, the first pre-commercial floating wind farm Hywind Scotland has been commissioned in 2017 and several more are projected to be constructed between 2018 and 2020 [4]. However, in order to reach commercial application, floating offshore wind turbines (FOWTs) need to solve not only the technological challenges faced by its bottom-fixed counterparts but also provide an economic alternative [3]. The levelized cost of energy (LCOE) is generally used to compare power generation technologies [5].

FOWTs possess the potential to provide competitive LCOE values by having the ability to harness the best possible wind resources without depth constraints and applying larger wind turbines to increase power generation [4]. Furthermore, the ability to mount the turbine on the floating substructure dockside and to tow the fully assembled structure by tug boats to the offshore site provides a significant potential for cost reduction along the life cycle, because expensive heavy lift jack-up vessels are avoided [2]. However, since only a few prototypes have been constructed so far, there is a lack of information on the LCOE of large scale floating offshore wind farms (FOWFs). Myhr et al. [6] have estimated in 2013 the LCOE for a number of different FOWT concepts made of steel and supporting a 5MW wind turbine.

The findings have shown LCOE values ranging between 106.3€/MWh and 287.8€/MWh, which appear unfavorable in comparison to the cost of current bottom-fixed offshore wind farms [7]. Further research has been proposed to investigate possible cost reductions and to study the impact of different site conditions. Castro et al. [8, 9] have developed in 2013 a methodology for the economic evaluation of FOWFs. The emphasis has been more on the modeling of the life cycle cost and less on the computation of the power generation in the system. For instance, the power losses due to the wake effect in the wind farm have not been considered. Ebenhoch et al. [10] have calculated in 2015 the LCOE of a FOWF based on a 4MW monolithic Spar buoy concept. The LCOE obtained at 175.5€/MWh has been significantly higher than estimated benchmark values for bottom-fixed structures in shallow waters [10]. The high LCOE value may has been due to the lack of information on the cost structure of FOWFs and several assumptions that have been made in the LCOE estimation. For instance, the operation and maintenance costs have been based on estimations for bottom-fixed offshore wind farms and the decommissioning cost has been considered as a percentage of the capital expenses. Hence, the advantages that FOWTs provide to reduce costs in these life cycle phases have not been taken into account [11]. Besides that, the energy generation and losses in the system have been based on gross load factors and efficiency rates from literature and have not been optimized for the specific location [12].

Following the work done and the proposal for further investigation, the aim of this paper is to provide a comprehensive LCOE calculation for state-of-the-art commercial scale FOWFs based on cost data provided by industrial and academic FOWT developers. The LCOE computation involves both a detailed life cycle cost and energy loss calculation of the system. Furthermore, three different FOWT concepts are analyzed, namely Semi-submersible, TLP and Spar, representing the most promising designs in the sector. Besides that, concrete as well as steel structures are included to represent both manufacturing materials. The calculation is performed for three different offshore locations to study the effect of metocean conditions on the LCOE. Moreover, FOWTs with a rated capacity of 10MW are considered to represent the trend towards larger offshore wind turbines. A sensitive analysis of 325 input parameters is performed to identify the ones that most influence the LCOE, which provides an useful insight for developers and researchers for further cost reductions.

This paper is organized as follows. In Section 2, the methodologies are presented that are applied in the LCOE calculation and sensitivity analysis. In Section 3, a description is provided of the different FOWT concepts that are considered as well as the offshore locations and the associated FOWF configurations. Section 4 presents the results of the LCOE calculation and the sensitivity analysis. A conclusion of the main findings is given in Section 5.

2. Methodology

This paper is partially based on the work performed in the LIFES50plus project [13]. Two of the four concepts studied in the project are considered in this analysis. However, a third concept has been added to represent the whole range of the main FOWT designs available in the market. The analysis is performed by using the tool FOWAT (Floating Offshore Wind Assessment Tool), which was developed within the project. A detailed description of the methodology and the tool is provided by Benveniste et al. [14]. However, an outline of the methodology is given next in order to provide the background for the rest of the paper.

2.1. Levelized cost of energy

The LCOE calculation is a method used to obtain the cost of one unit energy produced and is typically applied to compare the cost competitiveness of power generation technologies. The LCOE model sets in relation the life cycle costs (LCCs) to the electrical energy provided (E_{el}) as follows [5]:

$$LCOE = \frac{LCC}{E_{\mathrm{el}}} = \frac{\sum_{t=1}^{n} \frac{CAPEX_0 + OPEX_{\mathrm{t}} + DECEX_{\mathrm{n+1}}}{(1+r)^{\mathrm{t}}}}{\sum_{t=1}^{n} \frac{E_{\mathrm{t}} + L_{\mathrm{t}}}{(1+r)^{\mathrm{t}}}}. \tag{1}$$

The LCCs include all costs occurring in the lifetime of the FOWF such as the capital expense (CAPEX), the cost during the operation and the maintenance phase (OPEX) as well as the decommissioning expense (DECEX) at the end of lifetime [12]. CAPEX includes the costs related to development, manufacturing, transportation and installation of the wind farm. These costs are also defined as investment costs since they occur at the beginning of the project before the wind farm starts to generate energy.

OPEX contains the costs related to operation and maintenance (O&M) activities during the lifetime of the project and DECEX represents the costs occurring at the end of the lifetime for the decommissioning of the wind farm [12]. The total LCCs are obtained as the sum of all phases and as shown in Eq. (2) [14].

$$LCC = C_{\text{Dev}} + C_{\text{Manuf}} + C_{\text{Transport}} + C_{\text{Instal}} + C_{\text{O\&M}} + C_{\text{Decom}} \tag{2}$$

The development phase (C_{Dev}) includes all activities related to the initial development and design of the FOWF up to the point at which the official orders for production and purchasing are made [15]. This first phase is highly important for the projects outcomes since a well-planned design and schedule will enable a construction on time and with low added costs [16]. The development costs are considered in the LCC calculation as a percentage of the CAPEX. The manufacturing cost (C_{Manuf}), as defined in Eq. (3), includes the expenses for either the acquisition or production of each of the components of the FOWF, which include the turbines, floating substructures, anchor and moorings, substations and power cables [8].

$$C_{\text{Manuf}} = C_{\text{Turb}} + C_{\text{Substruct}} + C_{\text{Anchor}} + C_{\text{Mooring}} + C_{\text{Substation}} + C_{\text{Cable}} \tag{3}$$

Transportation is considered between the fabrication site, the assembly port and the offshore site. The total transportation cost ($\text{C}_{\text{Transport}}$) is dependent on vessel specific parameters such as the day rate and fuel consumption, the rental time and usage of the vessel as well as mobilization and demobilization cost [17]. No transportation is considered for delivering the components from the supplier to the port, because this cost is included in the purchasing price. However, costs accounting for port activities such as the utilization of cranes and auxiliary means as well as the lease of area for storage and loading purposes are considered [18]. The total installation cost (C_{Instal}), as defined by Eq. (4), consists of the individual cost for the installation of the offshore turbine and the floating substructure ($\text{C}_{\text{Turb\&FS}_{\text{instal}}}$), the pre-installation of the anchor and mooring system ($\text{C}_{\text{A\&M}_{\text{instal}}}$) as well as the inter-array and export cable laying ($\text{C}_{\text{IAC\&EX}_{\text{instal}}}$). Besides that, the offshore and onshore substation cost ($\text{C}_{\text{Subst}_{\text{instal}}}$) are also considered in the installation phase as well as the commissioning ($\text{C}_{\text{Commission}}$) of the complete wind farm [14].

$$C_{\text{Instal}} = C_{\text{Turb\&FS}_{\text{instal}}} + C_{\text{A\&M}_{\text{instal}}} + C_{\text{IAC\&EX}_{\text{instal}}} + C_{\text{Subst}_{\text{instal}}} + C_{\text{Commission}} \tag{4}$$

The installation costs of each component are based on the vessel used for the installation as well auxiliary means and divers [17]. The O&M begins after the commissioning of the FOWF and the associated costs occur annually. The operation expenses include, for example, insurances, transmission charges and leases [16]. The maintenance is used to ensure a high availability of the FOWF and to reduce the downtime. It includes preventive and corrective maintenance. Preventive maintenance cost covers all activities that aim to avoid a failure of a machine such as inspections and replacements of wear parts or lubricants. An accurate planning of the maintenance activities is crucial to limit maintenance costs and prevent breakdowns of the machines. Corrective maintenance, on the other hand, responds to the failure of a component of the wind farm. In contrast to preventive maintenance, corrective maintenance is carried out after a failure has happened and includes the repair or replacement of a component [19]. The total O&M costs ($\mathrm{C_{O\&M}}$) consist of the sum of operation cost ($\mathrm{C_{Operation}}$), preventive ($\mathrm{C_{Prev\_maint}}$) and corrective ($\mathrm{C_{Corr\_maint}}$) maintenance cost as defined by Eq. (5) [14].

$$C_{\mathrm{O\&M}} = C_{\mathrm{Operation}} + C_{\mathrm{Prev\_maint}} + C_{\mathrm{Corr\_maint}} \tag{5}$$

The preventive maintenance cost (Eq. (6)) is based on the vessels day rate ($\mathrm{C_{vessel}}$), diver expenses ($\mathrm{C_{Diver}}$) as well as the number of maintenance activities per year ($\mathrm{N_{activities}}$), which is an indicator for the frequency of maintenance activities. Furthermore, the cost for the replacement of wear parts ($\mathrm{C_{wear}}$) is considered [14].

$$C_{\mathrm{Prev\_maint}} = \sum (C_{\mathrm{vessel}} * t_{\mathrm{vessel}} + C_{\mathrm{fuel}} * L_{\mathrm{fuel}} + C_{\mathrm{wear}} + C_{\mathrm{Diver}}) * N_{\mathrm{activities}} \tag{6}$$

Floating wind turbines posses the ability to be towed back to port for major corrective maintenance [19]. This allows the use of smaller tug boats instead of heavy lift jack-up vessels. The corresponding calculation method of the costs is similar to the preventive maintenance with the difference that the failure rate ($\mathrm{F_{rate}}$) is used as an indicator for the maintenance frequency. In addition, costs are considered that occur when maintenance is performed in the port such as the use of cranes or auxiliary equipment. Eq. (7)) displays the calculation of the total corrective maintenance costs [14].

$$\begin{aligned} C_{\mathrm{Corr\_maint}} = \sum (&C_{\mathrm{vessel\&cranes}} * t_{\mathrm{vessel\&cranes}} + C_{\mathrm{fuel}} * L_{\mathrm{fuel}} \\ &+ C_{\mathrm{component}} + C_{\mathrm{Diver}}) * F_{\mathrm{rate}} \end{aligned} \tag{7}$$

The decommissioning of the FOWF is performed after the lifetime end. In general, the offshore wind farm owner is obligated to remove all structures that were built and to clear the site. However, it also depends on national regulations and in some cases a decommissioning of all components might not be required when associated risks are too high or the impact of remaining structures is not significant [17]. Decommissioning can be considered as a reversed installation process and includes the disassembly of the wind farm as well as the transportation back to the port. Besides that, the final treatment of the different components of the FOWF is considered as well as the clearance of the site with its associated costs $C_{\mathrm{Treatment}}$ and C_{Clear}, respectively [17]. The total decommissioning costs (C_{Decom}) can be obtained as defined in Eq. (8)) [14].

$$\begin{aligned} C_{\mathrm{Decom}} = {} & C_{\mathrm{Turb\&FS_{decom}}} + C_{\mathrm{Anchor\&Mooring_{decom}}} + C_{\mathrm{Cable_{decom}}} + C_{\mathrm{Substation_{decom}}} \\ & + C_{\mathrm{Clear}} + C_{\mathrm{Treatment}} \end{aligned} \tag{8}$$

Since the LCCs occur in different years (t), they have to be discounted to their present value by applying a discount rate (r). The discount rate has a large influence on the LCOE and represents the market value of equity and debt. Furthermore, the project risk and return yield are considered. The rate is, therefore, also known as weighted average cost of capital (WACC) and has typically a value between 8% and 12% for offshore wind farm investments [6].

$$WACC = \frac{E}{E+D} * k_{\mathrm{E}} + \frac{D}{E+D} * k_{\mathrm{D}} \tag{9}$$

Eq. (9)) displays the WACC calculation, where E is the equity of the company, D is the debt, k_{E} represents the cost of equity and k_{D} the cost of debt [20]. The energy provided is the denominator of the LCOE equation (Eq. (1)). It refers to total energy generated (E_t) during the lifetime minus the energy losses (L_t) that occur in generation, collection and transmission of the energy [21]. Fig. 1 displays the losses in the system that are considered in the model.

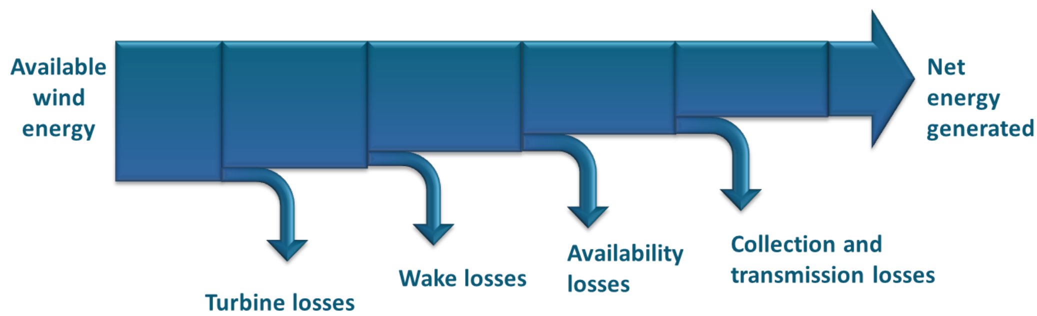


Fig. 1. Energy losses considered in the LCOE calculation

The available wind energy ($E_{available}$) is defined in this paper as the amount of energy extractable by the FOWT based on the characteristics of the wind turbine and the metocean conditions. It is obtained as following:

$$E_{\text{available}} = \sum P_{\text{metocean}} * H_{\text{metocean}} * 8760, \tag{10}$$

where $P_{metocean}$ is the power obtained for a specific metocean condition, defined by a certain wind speed and a particular wave height. The occurrence probability per year of this particular metocean condition is considered by $H_{metocean}$. The power generated by the FOWT can be calculated by:

$$P_{\text{metocean}} = \frac{1}{2}\, \rho_{\text{a}}\, A_{\text{rotor}}\, C_{\text{p}}(\lambda, \beta)\, v_{\text{wind}}{}^{3}, \tag{11}$$

where ρ_a represents the air density, A_{rotor} is the rotor swept area, C_p the power coefficient and v_{wind} the wind speed at hub height. The power coefficient depends on the blade tip-speed ratio λ and the blade pitch angle β [22]. The turbine losses illustrated in Fig. 1 account for the electrical losses in the generator and power electronics of the wind turbine and which are not included in the power power coefficient. A further energy loss considered is based on the wake effect from neighboring wind turbines in the wind farm. The wake losses are computed according to the WAsP Park-model, which is a row-based calculation of power loss and based on the single-turbine wake model of Jensen [23], supplemented by an empirical model wake-interaction and combined with the local statistical distribution of the mean wind speed. A more detailed explanation of the model and the obtained wake losses is given by Bredmose [24].

The availability (K) is defined as the proportion of time a wind farm is capable to produce energy and is obtained as follows [25]:

$$K = 1 - \frac{T_{\mathrm{D}}}{T_{\mathrm{N}}}, \tag{12}$$

where T_N is the nominal time and T_D the downtime. The nominal time represents the total time period without any interruption. The downtime is the time the floating offshore wind farm is not producing energy and thus results in a loss of energy production. The downtime is caused by failures and breakdowns of components in the wind farm such as the wind turbines and substations [26]. The total loss in energy production based on the availability of the floating wind farm is considered as an efficiency rate. Since so far no floating offshore wind farms exists that have been operated for a longer period, the availability rate of bottom-fixed offshore wind farms is considered. Collection and transmission losses represent the cumulative energy losses that occur in the power cables due to the resistive heating. The power loss of an individual cable can be computed by:

$$P_{\mathrm{cable\ loss}} = {I_{\mathrm{cable}}}^2 * R_{\mathrm{cable}} * l_{\mathrm{cable}}, \tag{13}$$

where I_{cable} represents the current flowing through the cable, R_{cable} the resistance and l_{cable} the length of the cable [27].

2.2. Sensitivity analysis

A sensitivity analysis is generally used to identify how the output of a model reacts to variations in model inputs given by variables or parameters [28]. In this paper, output is defined as the value of the LCOE of a FOWF in €/MWh. The inputs are parameters that are needed for the calculation of the LCOE such as costs, financial variables and energy related parameters. The quantification of uncertainty in the input is given by a specific range of variation, which is in this study 50% above and below the mean value. The specific range must be, however, the same for all input parameters to ensure that the results are comparable. There exist also a number of different methods to perform a sensitivity analysis [28]. The type that is applied in this analysis is the One-at-a-time (OAT) method. OAT is one of the simplest and most common approaches, which implies to vary one parameter at a time while holding the others fixed. This approach is repeated for all input parameters considering the defined uncertainty range [29].

The obtained results can be presented in form of a tornado diagram to represent the effect on the LCOE by the variation of input data. A threshold value can then be defined that filters the results. For example, in this analysis a minimum variation of 1% is required to be counted as a significant input parameter. The filtered results are further studied by defining reasonable variation ranges in order to obtain the actual influences on the LCOE and to examine the output based on best and worst case scenarios [30]. This can be of great interest for the floating wind technology in order to highlight the performance limits and to identify potential cost reductions.

3. Description of concepts and offshore sites

3.1. Floating offshore wind turbine concepts

In this paper, the three most common types of floating substructures are studied. These are the Semi-submersible, Tension Leg Platform (TLP) and Spar. The cost data used for this study has been provided by the respective concept designer. Fig. 2 illustrates the FOWT designs.

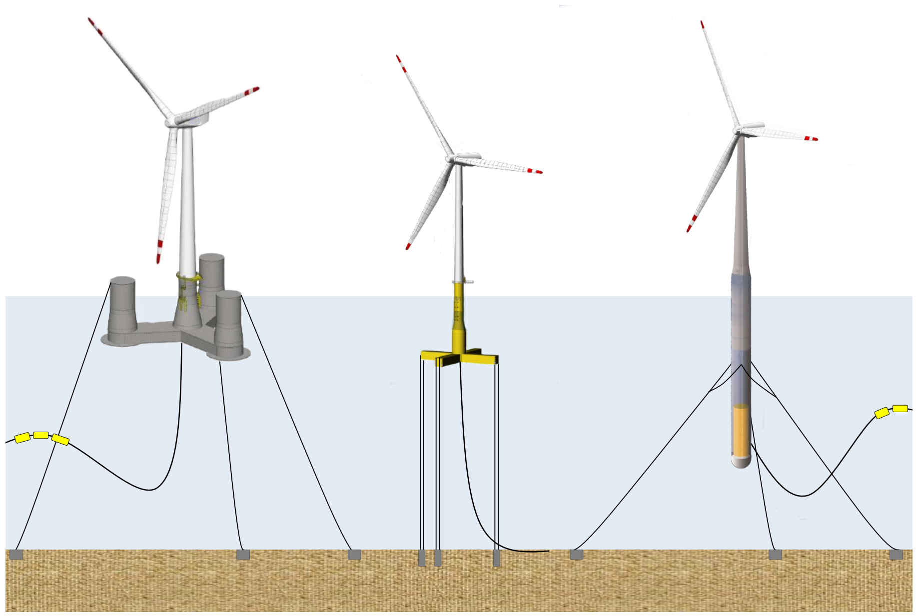


Fig. 2. Illustration of floating offshore wind turbine concepts. From left: Semi-submersible Concrete based on OO-Star Wind Floater [31], TLP Steel based on TLPWIND [32] and Spar Concrete based on Windcrete [33].

All three concepts support the DTU 10MW reference wind turbine. The horizontal upwind turbine has been developed by the Technical University of Denmark (DTU) and consists of a 3-bladed rotor, medium speed drivetrain with a multiple stage gearbox and a variable speed collective pitch control. The hub height is 119m and the rotor has a diameter of 178.3m. Further information about the wind turbine is provided by Bak et al. [34]. The tower and associated costs have been adjusted to each of the FOWT designs.

The semi-submersible floating substructure gains stability through distributed buoyancies and uses the weighted water plane area for the righting moment. This tends to lead to a larger surface structure, which involves the use of more material in comparison to other concepts [35]. The concept considered in this study is made of concrete and can be constructed locally worldwide [36]. Fabrication of the hull can be done on floating barges, in a dry dock or on a quay. The installation of the turbine is performed at quayside, which allows to avoid the use of expensive offshore cranes. The low draft allows a simple transportation with tug boats of the complete FOWT and a flexible application also in lower water depths [36]. As soon as it arrives at the offshore site, the floater will be connected to the pre-installed mooring system at the offshore site, which consists either of catenary or taut spread mooring lines. The drag anchor is commonly applied to these mooring systems, but the final choice depends on the soil conditions at the specific site [37]. The concrete structure requires few on-site inspections and the required preventive maintenance activities can be performed along with the turbine maintenance, which reduces costs. In addition, it can be towed back to shore by tug boats in case of a major repair due to its floatability. The decommissioning follows the same principle as the installation and disassembled concrete components may be reused at a suitable location [36].

The TLP requires a stabilization of the floating substructure by mooring lines. It consists of a semi-submerged buoyant structure that is anchored to the seabed by tension leg moorings. The low draft and high stability allows for a smaller and lighter structure as well as applications in shallow waters. However, the concept increases the stresses on the tendons and anchor system. Suction or pile anchors are commonly used to bear the stresses from the taut mooring lines [38]. The dependence on the taut moorings for stabilization requires a special purpose-built vessel for transportation and installation [3]. The TLP design considered in this study uses steel as main construction material [39]. After the decommissioning of the floating substructure, steel components can be processed and sold as recycled material [40].

The Spar is a cylindrical structure that gains its stability from having the center of gravity lower in the water than the center of buoyancy. It uses ballast weights in the lower part of the structure, which creates a righting moment and high inertial resistance to pitch and roll [3]. Due to the large draft requirement the floater concept tends to be applied in waters deeper than 90m and can cause some challenges in the installation phase [35]. The Spar concept considered in this paper is made of concrete and encourages the use of low cost materials, local construction processes and low maintenance needs. The substructure can be built in a dry dock and in a horizontal position by using a slipform, which avoids the presence of concrete joints. After floating the dock, the substructure tug boats tow the structure to the installation site. The erection of the Spar and the installation of the wind turbine are performed offshore by submerging the structure and exchanging the ballast material. A catamaran ship can be applied for this process instead of heave floating cranes, which reduces installation costs. After erection, the SPAR is connected to the pre-installed mooring system, which consists of three catenary mooring lines [41]. The anchor type that is being used depends mainly on the seabed conditions and can range from drag anchors for sandy sites to suction pile anchors for layered and rocky soils. The decommissioning follows the same principal as the installation process and concrete material may be reused or sold for other purposes [41]. Further information about the specific floating wind turbine concepts can be found on the respective websites of the concept developers, which are listed in the references [31, 33, 32].

3.2. Offshore sites

The metocean conditions of an offshore site have a significant influence on the design, cost and performance of FOWTs [42]. For instance, the type of seabed influences the choice of anchor and the mooring line length depends largely on the water depth. Furthermore, the dimensions and design of the floating substructure have to be carefully chosen in order to withstand even the most extreme environmental loads of a specific site [38]. Besides that, the available wind resources are highly important in order to maximize energy generation. In this study, three offshore locations are considered to represent different metocean conditions namely Golfe de Fos (moderate), Gulf of Maine (medium) and West of Barra (severe). In addition, the sites are chosen based on potential deployment areas of the three FOWT concepts and where political support is expected for offshore wind.

The availability of metocean data has also been essential for the selection process. Table 1 summarizes the characteristics and Fig. 3 (a,c,e) displays the location of the wind farm with relevant water depths.

Table 1. Offshore sites characteristics

	Golfe de Fos	Gulf of Maine	West of Barra
Country	France	USA	Scotland
Reference location	Marseille	Portland	Barra
Ocean	Mediterranean Sea	Atlantic	Atlantic
Metocean conditions	Moderate	Medium	Severe
Design water depth (m)	70	130	100
Wind speed 50 years (m/s)	37	44	50
Mean wind speed at 100m (m/s)	>10	10.18	11.26
Sign. wave height 50 years (m)	7	10.48	14.27
Transmission length* (km)	38	57.8	180
Soil type	Sand/Clay	Sand/Clay	Rock/Basalt

*Distance between offshore and onshore substation

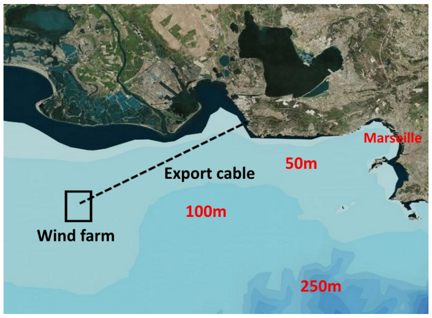
Golfe de Fos has been chosen to represent moderate metocean conditions with a design water depth of 70m and a 50-year wind speed at hub of 37m/s [43]. Despite not having deployed any bottom-fixed offshore wind turbines to date, France is increasingly promoting the development of floating wind technology. A 2MW full-scale prototype has been installed in May 2018 and four pre-commercial FOWFs are expected to be commissioned by 2020/21. Having suitable offshore sites in both the Mediterranean Sea and the Atlantic Ocean, France has proposed in his current multi-annual energy program to develop up to 6GW of bottom-fixed offshore wind and 2GW of floating wind and tidal projects by 2025/26 [44]. Gulf of Maine site is located about 57.8km off Portland in the Northeast coast of the USA. It represents medium metocean conditions with 44m/s of 50 years wind speed and a water depth of 130m [43]. Floating wind activity can be tracked back in the state of Maine as early as 2013, where a small prototype of the VolturnUS concrete Semi-submersible concept was installed. It represented also the first offshore wind turbine deployed in US waters. Two 6MW full-scale models of this concept are expected to be commissioned by 2020 off the coast of Maine followed by a potential commercial deployment [44]. West of Barra site is situated 19km West of Barra Island in the Atlantic Ocean. It has the harshest conditions and highest wind resources with a 50-year wind speed of 50m/s and 100m design water depth.

Furthermore, basalt is present at this location, whereas the soil of the other two sites consists of a mixture of sand and clay [43]. Scotland has large potential for floating wind deployment with attractive near-shore deep water sites and suitable metocean conditions. It is home to the world's first floating wind farm Hywind Scotland, which was commissioned in 2017 and a second project consisting of the 50MW Kincardine floating wind farm is expected to be completed by 2019/20. Floating wind could benefit from the experience and supply chain of UK's offshore wind industry and could play a large part in Scotland's target to generate all of its electricity from renewable sources by 2020 [44]. A detailed description of the three offshore sites and environmental conditions is given by Gomez et al. [43].

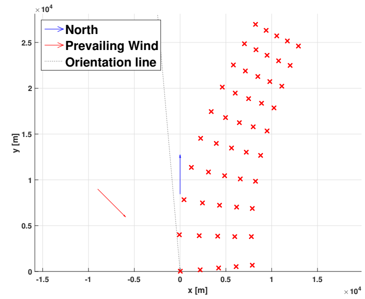
3.3. Wind farm definition and general parameters

A FOWF is considered with 50 offshore wind turbines and a nominal power capacity of 500MW. The selected transmission technology is HVAC with the collection grid voltage operating at 66kV and the transmission voltage at 220kV. The position of the wind turbines within the wind farm layout is the same for all concepts and, therefore, provokes the same wake losses. However, the connection of the floating wind turbines and the position of the offshore substation are defined individually by each concept designer, which cause the total power cable losses to be slightly different. Fig. 3 (b,d,f) presents the wind farm layouts of the three offshore sites. The wind turbines are placed in direction to the prevailing winds at each site.

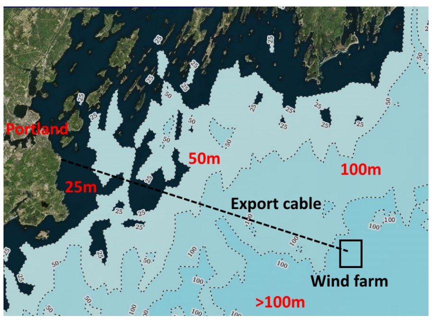
The interconnection of the wind turbines is realized by a combination of dynamic and static power cables, where the dynamic part is connected to the turbines and the static part is laying on the seabed. The cost of the offshore substation is estimated for different water depths and reactive power compensation is adjusted according to the distance to shore. Advantage is taken of existing electrical infrastructure concerning the onshore substation. However, for the case of West of Barra a larger investment is required, because no suitable infrastructure exists at the location. In addition, common parameters are defined that are used for all study cases. For instance, the discount rate is set to 10%, which represents a typical value for offshore wind farm projects and a lifetime of 25 years is chosen.



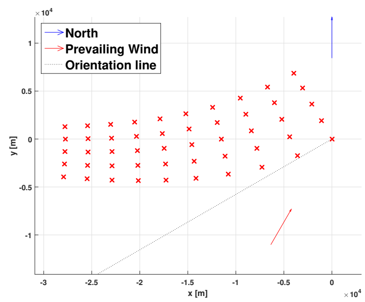
(a) Golfe de Fos site



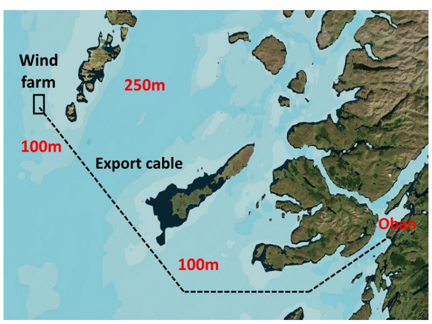
(b) Golfe de Fos layout



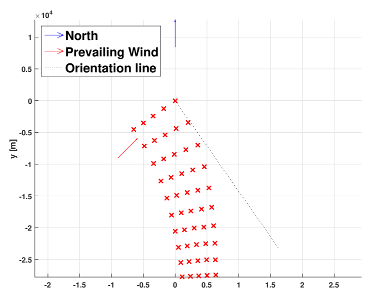
(c) Gulf of Maine site



(d) Gulf of Maine layout



(e) West of Barra site



(f) West of Barra layout

Fig. 3. Offshore sites and layouts

4. Results

The input data used in study has been provided by the respective concept designer and thus the results are affected by the accuracy and source of the data. Furthermore, a general conclusion for FOWT concepts cannot be given since they vary widely by their technical specifications and cost composition.

Besides that, the concepts compared in this paper are on different technical and commercial readiness levels, which involve a different degree of uncertainty in the data. Therefore, the objective of this paper is not to assess the feasibility of the concepts nor the LCOE values, but rather to analyze the sensitivity of the LCOE in relation to input parameters.

4.1. Levelized cost of energy

The results of the levelized cost of energy calculation for the different offshore sites and floating offshore wind turbine concepts are presented in Fig. 4. The Spar buoy concept could not be analyzed for Golfe de Fos because of the deep draft and the low water depth available at this offshore site. The LCOE values are shown with and without offshore transmission cost to consider the different policies that are in place in the countries regarding transmission assets. Besides that, this allows a better comparison of the FOWT concepts since the transmission assets are considered as common components and possess similar costs.

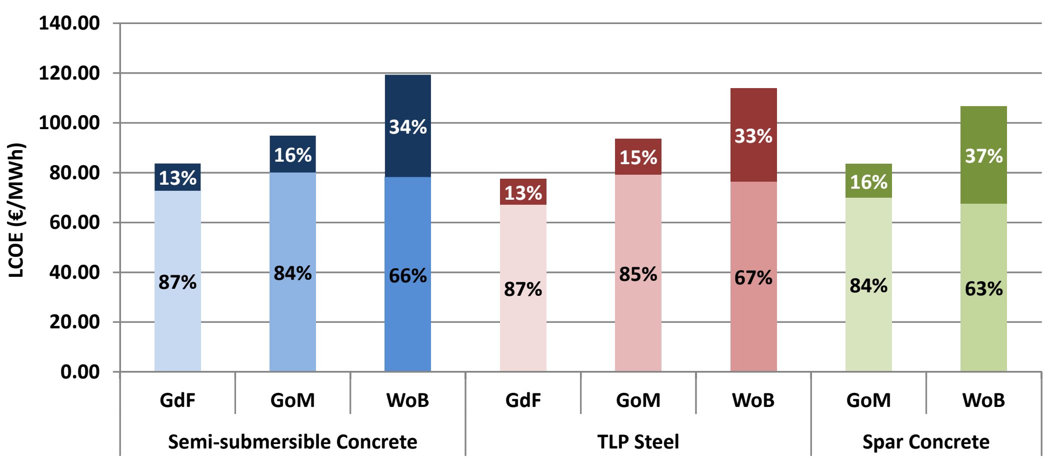


Fig. 4. LCOE results for each concept and offshore site. The upper parts of the bars represent the portion of transmission asset costs of the LCOE.

The values for the FOWF obtained in this study range from as low as 77€/MWh for the TLP FOWT concept in Golfe de Fos including offshore transmission costs to 119€/MWh for the Semi-submersible FOWT concept in West of Barra. A significant portion of the LCOE represents the cost of the offshore transmission assets, which is influenced by the different sites and highlighted in the figure. For instance, for the West of Barra case the portion of the transmission cost reaches up to 37% for the Spar concept, 34% respectively for the Semi-submersible FOWT concept and 33% for the TLP concept. The high portion is based on the long export cable needed for the remote offshore site with respective investment costs and energy losses. Furthermore, the cost of the substation increases with the distance due to the larger investment required for reactive power compensation in the HVAC transmission. The difference in the offshore transmission costs among the three FOWF designs is based on the different positioning of the offshore substation within the wind farm layout. It influences the distance to shore and consequently the length of the export cable, the cost of the offshore substation as well as other LCCs such as transportation, maintenance and decommissioning. The LCOE results without offshore transmission assets demonstrate values, for instance, as lows as 67€/MWh for the TLP FOWT concept in Golfe de Fos. Next, Fig. 5 shows a LCOE comparison between different energy generation technologies.

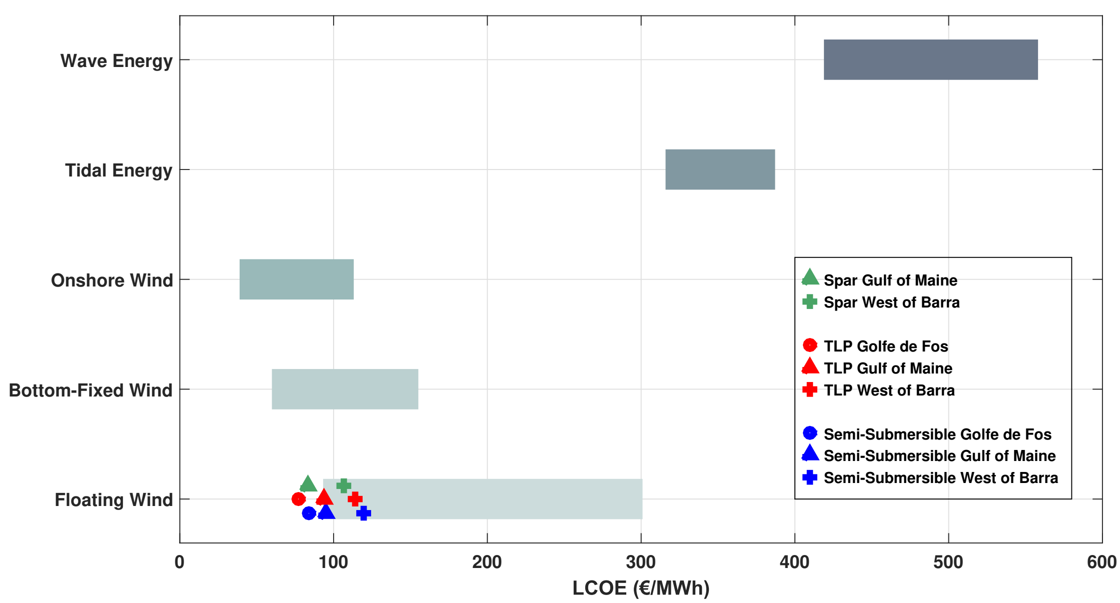


Fig. 5. LCOE comparison between energy generation technologies. Calculated values of TLP in red, Semi-submersible in blue and Spar in green. The reference LCOE range for floating offshore wind is based on Myhr et al. [6]. The range for wave and tidal energy is taken from the Carbon Trust [45], for bottom-fixed offshore wind from Kausche et al. [7] and for onshore wind from Duan [46].

The LCOE values calculated for the three offshore sites and for each of the floating wind turbine concepts are highlighted by colored symbols. Myhr et al. [6] has estimated the LCOE values for a number of different FOWT concepts and the results are taken as a reference range. It can be seen that the obtained LCOE values are in the lower part or even below the reference range, which demonstrates the high cost effectiveness of the studied concepts. Furthermore, Fig. 5 shows that floating offshore wind power can be a high competitive solution to conventional bottom-fixed offshore wind, where the LCOE is currently between 73€/MWh and 142€/MWh [7]. In addition, the obtained values are comparable to Contracts for Difference auction results recently published in the United Kingdom with commissioning years expected to be between 2021 and 2023 [47]. However, in order to be competitive in the long-term, floating wind energy needs to follow the cost reduction pathways that onshore and offshore wind energy have already experienced. Floating wind can also benefit from economies of scale of the well developed bottom-fixed offshore wind sector since many components are shared by both technologies. In addition, FOWTs have the advantage to be placed in locations with the best possible wind resources without depth constraints, which improves the capacity factor and leads to a lower LCOE [4]. Moreover, floating wind does not necessarily need to compete with bottom-fixed offshore wind turbines, because FOWTs possess its full potential at deep water locations (more than 60m), where conventional bottom-fixed substructures are unsuitable from a cost and technical perspective [3].

Ocean energy technologies, such as tidal and wave energy converters, are still at an early stage of development and have in comparison the highest cost of energy [48]. The Carbon Trust [45] has estimated the LCOE of tidal and wave energy at 329€/MWh to 374€/MWh and 432€/MWh to 545€/MWh, respectively. The higher cost of energy results from both lower capacity factors and a higher capital investment [49]. Furthermore, the rate of cost reduction is potentially lower since ocean energy can not benefit as much as floating offshore wind from an existing supply chain [45].

Fig. 6 shows a breakdown of the LCCs including offshore transmissions assets for the different FOWF concepts and offshore sites. The LCCs are represented by differently colored bars and the value for each of the offshore sites is highlighted by the horizontal lines. Manufacturing contributes by far the highest portion to the LCC for all sites and concepts. This could be expected because it includes the manufacturing cost of large components such as the wind turbines, substructures, power cables and substation.

Besides that, it includes the storage cost in the port as well as the load-out process. The larger investment required for the offshore transmission in West of Barra contributes to an increased manufacturing cost for this site.

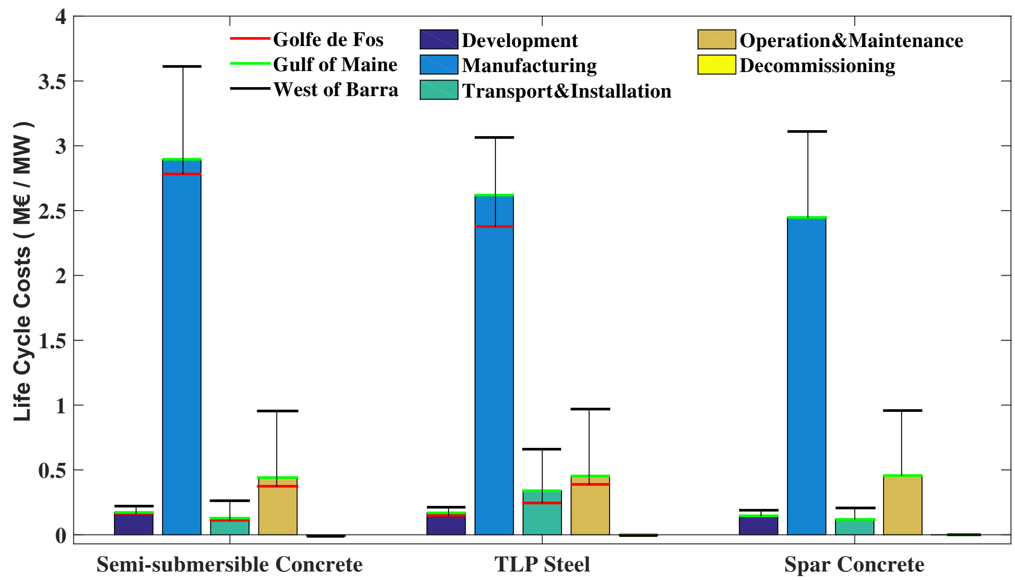


Fig. 6. Life cycle costs including transmission assets

Furthermore, it can be observed that transportation and installation costs have increased for West of Barra. Concerning the comparison among the FOWT concepts, the Spar obtains the lowest LCC due to the manufacturing cost reduction potential of concrete structures, simple anchor and mooring lines and a cost effective installation process. However, due to the large draft the Spar concept is not suitable for water depths below 90m, such as in Golfe de Fos. The Semi-submersible concept possesses larger manufacturing costs due to the greater dimensions but lower transportation and installation costs, since it can be towed by simple tug boats. Furthermore, parallel transportation and installation activities have been considered during the transportation and installation process. Thus, by slightly increasing the number of less costly tug boats, the rental time and overall cost could be reduced significantly. The TLP concept, on the other hand, requires a special purpose built barge for the offshore transportation due to its instability, which construction cost is included in the manufacturing life cycle.

By comparing West of Barra with Golfe de Fos and Gulf of Maine, it can be seen that this site requires a more robust substructure due to the severe metocean conditions. However, the required robustness of the floating substructures does not necessarily result in a significant cost increase. Only a 10% higher investment for the substructures is observable on average among the concepts. The site's environmental conditions have certainly a significant influence on the installation cost, because a larger and more specialized installation spread is required to install within reduced weather windows. Moreover, soil conditions in West of Barra are more challenging because the seabed consists of rocks while at the other sites it is basically sand and mud. This requires a different anchor type and depending on the FOWT concept, it can impact the manufacturing and especially the installation cost of anchor and mooring lines.

4.2. Sensitivity analysis

In this analysis, 325 parameters such as costs, financial variables and energy related parameters have been considered as sensitivity parameters to assess their influence on the LCOE of a FOWF. The parameters are based on the input data provided by the concept designers for the design specific components and other parameters are defined for the common components. A complete list of the parameters is provided by Benveniste et al. [50]. The parameters that most influence the LCOE, based on the minimum 1% criteria, are shown in Tables 2 and 3.

The results are shown at first for floating design dependent parameters and afterwards for the common parameters, which are based on the balance of plant, energy related and economic parameters. Table 2 shows that the parameters that most vary the LCOE across all concepts and offshore sites are capital cost related. This includes the cost of the substructure, inter-array power cable cost and length as well as mooring and anchor cost. However, it is also observable that the installation vessel day rate has an important influence on the LCOE. An increase or decrease of the substructure cost has by far the highest impact on the LCOE with a variation on the LCOE value ranging from 4.11% for the Spar buoy concept in West of Barra to over 12.41% for the Semi-submersible in Golfe de Fos. Furthermore, the higher variation by the Semi-submersible concept reflects the higher construction cost needed for that type of floating substructure. The mooring cost of the Spar buoy concept has also a significant influence on the LCOE based on the specific type of mooring line used for holding the structure in place.

Table 2. LCOE variation (%) by change of design dependent parameters by ±50%

Offshore site	Concept / Parameter variation	Semi-submersible Concrete -50%	Semi-submersible Concrete +50%	TLP Steel -50%	TLP Steel +50%	Spar Concrete -50%	Spar Concrete +50%
Golfe de Fos	Substructure cost	-12.41	+12.41	-8.24	+8.24		
	Inter-array cable length	-3.14	+3.15	-2.15	+2.16		
	Inter-array cable cost	-2.40	+2.40	-0.89	+0.89		
	Mooring cost	-1.61	+1.61	-1.42	+1.42		
	Installation vessel day rate	-1.07	+1.07	-2.75	+2.75		
	Anchor cost	-0.38	+0.38	-1.93	+1.93		
	Anchor&Mooring installation time	-0.29	+0.29	-1.67	+1.67		
Gulf of Maine	Substructure cost	-11.44	+11.44	-8.85	+8.85	-5.26	+5.26
	Inter-array cable length	-3.13	+3.14	-1.94	+1.95	-3.12	+3.16
	Inter-array cable cost	-2.45	+2.45	-0.94	+0.94	-1.88	+1.88
	Mooring cost	-1.99	+1.99	-1.47	+1.47	-4.42	+4.42
	Anchor cost	-0.43	+0.43	-2.00	+2.00	-0.88	+0.88
	Installation vessel day rate	-0.99	+0.99	-2.94	+2.94	-1.00	+1.00
	Anchor&Mooring installation time	-0.26	+0.26	-2.02	+2.02	-0.25	+0.25
West of Barra	Substructure cost	-9.15	+9.15	-7.15	+7.15	-4.11	+4.11
	Mooring cost	-3.01	+3.01	-1.03	+1.03	-4.10	+4.10
	Inter-array cable length	-2.28	+2.29	-1.30	+1.31	-2.60	+2.65
	Inter-array cable cost	-1.71	+1.71	-0.64	+0.64	-1.39	+1.39
	Anchor cost	-0.20	+0.20	-0.55	+0.55	-0.93	+0.93
	Installation vessel day rate	-1.03	+1.03	-5.12	+5.12	-0.79	+0.79
	Anchor&Mooring installation time	-0.43	+0.43	-4.67	+4.67	-0.25	+0.25

The results for the common parameters are presented in Table 3. The common parameters show that there is no large difference among the concepts on the LCOE variation. However, there is a difference among the offshore sites. Turbine and offshore substation cost cause clearly a large influence on the LCOE based on the capital intensive investment. The LCOE variation based on the export cable increases among the offshore sites. West of Barra requires the longest and thus most expensive export cable. The influence on the LCOE is, therefore, the highest for this location. The discount rate has by far the largest influence among all input parameters studied. A 50% increase or decrease of the mean value causes a variation of the LCOE by more than 30% for all study cases. Thus, a well-chosen discount rate is of significant importance for the LCOE calculation. Energy related parameters that were analyzed such as the overall net production, availability loss and turbine electrical losses possess also a larger impact on the LCOE. For this reason, energy losses in the system should tried to be minimized. Besides that, the maintenance has a larger impact on the LCOE. In particular, the number of preventive maintenance activities and the component repair cost.

Table 3. LCOE variation (%) based on change of common parameters by ±50%

	Concept	Semi-submersible Concrete		TLP Steel		Spar Concrete	
Site	Parameter variation	-50%	+50%	-50%	+50%	-50%	+50%
Golfe de Fos	Discount rate	-32.24	+36.34	-31.28	+35.49		
	Turbine cost	-20.09	+20.09	-21.75	+21.75		
	Energy production	+11.08	-9.07	+11.05	-9.04		
	Offshore substation cost	-3.75	+3.75	-4.06	+4.06		
	Turbine electrical losses	-3.08	+3.28	-3.07	+3.27		
	Availability loss	-2.56	+2.70	-2.56	+2.70		
	Operation cost	-2.56	+2.56	-2.76	+2.76		
	Development cost	-2.41	+2.41	-2.37	+2.37		
	Export cable length	-2.20	+2.34	-1.96	+2.04		
	Export cable cost	-1.58	+1.58	-1.44	+1.44		
	Preventive maintenance activities	-1.17	+1.17	-1.27	+1.27		
	Corrective maintenance failure rate	-1.14	+1.14	-1.23	+1.23		
	Lifetime	+1.85	-2.12	+1.90	-2.15		
Gulf of Maine	Discount rate	-31.76	+35.82	-31.33	+35.46	-30.50	+34.62
	Turbine cost	-18.95	+18.95	-19.22	+19.22	-21.68	+21.68
	Energy production	+11.08	-9.07	+11.06	-9.05	+11.11	-9.09
	Offshore substation cost	-3.80	+3.80	-3.85	+3.85	-4.35	+4.35
	Turbine electrical losses	-3.08	+3.29	-3.07	+3.28	-3.05	+3.25
	Export cable length	-3.57	+4.25	-3.40	+3.99	-3.19	+3.58
	Preventive maintenance activities	-2.48	+2.48	-2.51	+2.51	-2.84	+2.84
	Export cable cost	-2.40	+2.40	-2.31	+2.31	-2.26	+2.26
	Development cost	-2.38	+2.38	-2.36	+2.36	-2.31	+2.31
	Preventive maintenance repair cost	-2.14	+2.14	-2.17	+2.17	-2.45	+2.45
	Operation cost	-1.88	+1.88	-1.90	+1.90	-2.15	+2.15
	Corrective maintenance failure rate	-1.07	+1.07	-1.09	+1.09	-1.23	+1.23
	Lifetime	+1.83	-2.10	+1.86	-2.12	+1.86	-2.11
West of Barra	Discount rate	-29.19	+32.98	-28.73	+32.53	-27.95	+31.74
	Export cable length	-19.10	+73.23	-17.40	+58.21	-19.71	+73.15
	Turbine cost	-13.64	+13.64	-14.02	+14.02	-15.39	+15.39
	Energy production	+11.08	-9.06	+11.04	-9.04	+11.11	-9.09
	Export cable cost	-5.81	+5.81	-5.68	+5.68	-6.50	+6.50
	Operation cost	-4.96	+4.96	-5.10	+5.10	-5.60	+5.60
	Availability loss	-4.17	+4.55	-4.17	+4.55	-4.17	+4.55
	Turbine electrical losses	-3.49	+3.75	-3.41	+3.66	-3.44	+3.71
	Preventive maintenance activities	-3.04	+3.04	-3.12	+3.12	-3.43	+3.43
	Preventive maintenance repair cost	-2.71	+2.71	-2.79	+2.79	-3.06	+3.06
	Offshore substation cost	-2.64	+2.64	-2.71	+2.71	-2.98	+2.98
	Development cost	-2.19	+2.19	-2.17	+2.17	-2.12	+2.12
	Export cable installation vessel	-1.16	+1.16	-1.14	+1.14	-1.30	+1.30
	Lifetime	+1.71	-1.95	+1.72	-1.96	+1.72	-1.94

The corrective maintenance failure rate has also significant influence on the LCOE. For West of Barra, the operation cost shows a larger influence since transmission charges are required to be included at this site.

4.3. LCOE variation potential

This study is complementary to Section 4.2 as it presents the variation of the LCOE by applying uncertainty ranges defined by the FOWT concept designers and common ones. The ranges are applied on the parameters that most influence the LCOE and that were obtained in the previous section. This serves to identify how much the LCOE could actually vary based on uncertainty ranges defined by the designers. The parameter variation and LCOE results are listed in Table 4. Zero values in the table imply that no uncertainty ranges were defined for this parameter. The offshore site Golfe de Fos shows that the discount rate has the largest influence on the LCOE. For example, a 13.5% decrease of the LCOE is achievable by lowering the discount rate by 20%. However, when the discount rate is chosen too high, for example with a 20% increase, the LCOE can rise by about 14%. Furthermore, it can be observed that a decrease of 5% of the LCOE value can be reached by increasing the energy production by 5%.

The turbine supply costs and availability loss rate are also of significance for the LCOE. By lowering the turbine costs by 8% or reducing by half the availability loss rate, a reduction of up to 3% of the LCOE is achievable. The lifetime has also a significant influence. By extending the lifetime by 12%, the LCOE can be lowered by 2.7% because of the higher energy production. In case of a further expansion of the lifetime, investments would be required such as wind turbine component replacements that would negatively affect the LCOE. Besides that, the mooring system and floating substructure have been designed to a lifetime of 25 years and would require, depending on the concept, a redesign. The maximum parameter variation of the offshore substation is assumed to be 20%, which results in a LCOE decrease of 1.5% to 1.6% among the different concepts. However, according to a study performed by ORE Catapult [51], it is more likely that the cost of the offshore substation will increase than decrease. A 20% higher cost would result, for example, in the case of the Semi-submersible concrete floating wind turbine concept to a 1.5% increase of the LCOE.

Since the substructure cost represents a larger part of the CAPEX, it has also a significant influence on the LCOE. For instance, for the floating wind farm based on the Semi-submersible Concrete concept, a 20% cost reduction in the substructures can result into a 5% decrease of the LCOE value. Furthermore, it can be seen that based on the defined variation ranges for the cost of anchor and mooring as well as the power cables, a variation of the LCOE is not very significant (below 1%).

Table 4. LCOE variation based on change of individually defined parameters

Site	Concept / Parameter Variation	Semi-submersible Concrete LCOE % *(Parameter %)*	Semi-submersible Concrete LCOE % *(Parameter %)*	TLP Steel LCOE % *(Parameter %)*	TLP Steel LCOE % *(Parameter %)*	Spar Concrete LCOE % *(Parameter %)*	Spar Concrete LCOE % *(Parameter %)*
Golfe de Fos	Discount rate	-13.5 *(-20)*	+14.1 *(+20)*	-13.1 *(-20)*	+13.8 *(+20)*		
	Turbine cost	-3.1 *(-8)*	+6.2 *(+15)*	-3.4 *(-8)*	+6.2 *(+15)*		
	Substructure cost	-5.0 *(-20)*	+5.0 *(+20)*	0.0 *(0)*	0.0 *(0)*		
	Anchor cost	-0.1 *(-10)*	+0.1 *(+10)*	0.0 *(0)*	0.0 *(0)*		
	Mooring cost	-0.3 *(-10)*	+0.3 *(+10)*	0.0 *(0)*	0.0 *(0)*		
	Substation cost	-1.5 *(-20)*	+1.5 *(+20)*	-1.6 *(-20)*	+1.6 *(+20)*		
	Energy production	+5.3 *(-5)*	-4.8 *(+5)*	+5.2 *(-5)*	-4.7 *(+5)*		
	Availability loss	-2.6 *(-50)*	+2.7 *(+50)*	-2.6 *(-50)*	+2.7 *(+50)*		
	Turbine elec.loss	-1.1 *(-17)*	+1.1 *(+17)*	-1.1 *(-17)*	+1.1 *(+17)*		
	Export cable cost	-0.5 *(-17)*	+0.5 *(+17)*	-0.5 *(-17)*	+0.5 *(+17)*		
	Export cable length	-0.4 *(-10)*	+0.4 *(+8)*	-0.4 *(-10)*	+0.3 *(+8)*		
	Inter-array length	-2.0 *(-31)*	+0.9 *(+15)*	-1.3 *(-31)*	+0.6 *(+15)*		
	Inter-array cost	-0.7 *(-15)*	+0.7 *(+15)*	0.0 *(0)*	0.0 *(0)*		
	Instal.vessel day rate	-0.6 *(-30)*	+0.4 *(+20)*	-0.4 *(-7)*	+0.4 *(+7)*		
	Corr.maint.failure rate	-0.5 *(-20)*	+0.5 *(+20)*	-0.5 *(-20)*	+0.5 *(+20)*		
	Prev.maint.activities	-0.5 *(-20)*	+0.5 *(+20)*	-0.5 *(-20)*	+0.5 *(+20)*		
	Lifetime	+3.0 *(-12)*	-2.7 *(+12)*	+3.0 *(-12)*	-2.7 *(+12)*		
Gulf of Maine	Discount rate	-13.3 *(-20)*	+14.0 *(+20)*	-13.1 *(-20)*	+13.8 *(+20)*	-12.8 *(-20)*	+13.5 *(+20)*
	Turbine cost	-2.9 *(-8)*	+5.8 *(+15)*	-3.0 *(-8)*	+5.9 *(+15)*	-3.3 *(-8)*	+6.7 *(+15)*
	Substructure cost	-4.6 *(-20)*	+4.6 *(+20)*	0.0 *(0)*	0.0 *(0)*	-0.9 *(-9)*	+2.3 *(+22)*
	Anchor cost	-0.1 *(-10)*	+0.1 *(+10)*	0.0 *(0)*	0.0 *(0)*	-0.9 *(-50)*	+0.9 *(+50)*
	Mooring cost	-0.4 *(-10)*	+0.4 *(+10)*	0.0 *(0)*	0.0 *(0)*	-1.8 *(-20)*	+2.7 *(+30)*
	Substation cost	-1.5 *(-20)*	+1.5 *(+20)*	-1.5 *(-20)*	+1.5 *(+20)*	-1.7 *(-20)*	+1.7 *(+20)*
	Energy production	+5.3 *(-5)*	-4.8 *(+5)*	+5.2 *(-5)*	-4.7 *(+5)*	+5.3 *(-5)*	-4.8 *(+5)*
	Availability loss	-3.1 *(-50)*	+3.3 *(+50)*	-3.1 *(-50)*	+3.3 *(+50)*	-3.1 *(-50)*	+3.3 *(+50)*
	Turbine elec.loss	-1.1 *(-17)*	+1.1 *(+17)*	-1.1 *(-17)*	+1.1 *(+17)*	-1.1 *(-17)*	+1.1 *(+17)*
	Export cable cost	-0.8 *(-17)*	+0.8 *(+17)*	-0.8 *(-17)*	+0.8 *(+17)*	-0.8 *(-17)*	+0.8 *(+17)*
	Export cable length	-0.8 *(-11)*	+1.0 *(+12)*	-0.8 *(-11)*	+0.9 *(+12)*	-0.7 *(-11)*	+0.8 *(+12)*
	Inter-array length	-2.0 *(-31)*	+0.7 *(+12)*	-1.2 *(-31)*	+0.5 *(+12)*	-2.0 *(-31)*	+0.7 *(+12)*
	Inter-array cost	-0.7 *(-15)*	+0.7 *(+15)*	0.0 *0)*	0.0 *(0)*	-0.8 *(-20)*	+0.8 *(+20)*
	Instal.vessel day rate	-0.6 *(-30)*	+0.4 *(+20)*	-0.4 *(-7)*	+0.4 *(+7)*	-0.3 *(-15)*	+1.0 *(+50)*
	Corr.maint.failure rate	-0.4 *(-20)*	+0.4 *(+20)*	-0.4 *(-20)*	+0.4 *(+20)*	-0.5 *(-20)*	+0.5 *(+20)*
	Prev.maint.activities	-1.0 *(-20)*	+1.0 *(+20)*	-1.0 *(-20)*	+1.0 *(+20)*	-1.1 *(-20)*	+1.1 *(+20)*
	Lifetime	+3.0 *(-12)*	-2.7 *(+12)*	+3.0 *(-12)*	-2.7 *(+12)*	+3.0 *(-12)*	-2.7 *(+12)*
West of Barra	Discount rate	-12.3 *(-20)*	+12.9 *(+20)*	-12.1 *(-20)*	+12.7 *(+20)*	-11.8 *(-20)*	+12.4 *(+20)*
	Turbine cost	-2.1 *(-8)*	+4.2 *(+15)*	-2.1 *(-8)*	+4.3 *(+15)*	-2.4 *(-8)*	+4.7 *(+15)*
	Substructure cost	-3.7 *(-20)*	+3.7 *(+20)*	0.0 *(0)*	0.0 *(0)*	-0.7 *(-9)*	+1.8 *(+22)*
	Anchor cost	-0.1 *(-10)*	+0.1 *(+10)*	0.0 *(0)*	0.0 *(0)*	-0.9 *(-50)*	+0.9 *(+50)*
	Mooring cost	-0.6 *(-10)*	+0.6 *(+10)*	0.0 *(0)*	0.0 *(0)*	-1.6 *(-20)*	+2.5 *(+30)*
	Substation cost	-1.1 *(-20)*	+1.1 *(+20)*	-1.1 *(-20)*	+1.1 *(+20)*	-1.2 *(-20)*	+1.2 *(+20)*
	Energy production	+5.3 *(-5)*	-4.8 *(+5)*	+5.2 *(-5)*	-4.7 *(+5)*	+5.3 *(-5)*	-4.8 *(+5)*
	Availability loss	-4.1 *(-50)*	+4.6 *(+50)*	-4.2 *(-50)*	+4.6 *(+50)*	-4.1 *(-50)*	+4.6 *(+50)*
	Turbine elec.loss	-1.2 *(-17)*	+1.2 *(+17)*	-1.2 *(-17)*	+1.2 *(+17)*	-1.2 *(-17)*	+1.2 *(+17)*
	Export cable cost	-2.0 *(-17)*	+2.0 *(+17)*	-1.9 *(-17)*	+1.9 *(+17)*	-2.2 *(-17)*	+2.2 *(+17)*
	Export cable length	-2.2 *(-4)*	+1.0 *(+2)*	-1.9 *(-4)*	+0.9 *(+2)*	-2.2 *(-4)*	+1.0 *(+2)*
	Inter-array length	-1.6 *(-34)*	+0.8 *(+18)*	-0.9 *(-34)*	+0.5 *(+18)*	-1.8 *(-34)*	+1.0 *(+18)*
	Inter-array cost	-0.5 *(-15)*	+0.5 *(+15)*	0.0 *(0)*	0.0 *(0)*	-0.6 *(-20)*	+0.6 *(+20)*
	Instal.vessel day rate	-0.6 *(-30)*	+0.4 *(+20)*	-0.7 *(-7)*	+0.7 *(+7)*	-0.3 *(-15)*	+0.8 *(+50)*
	Corr.maint.failure rate	-0.3 *(-20)*	+0.3 *(+20)*	-0.4 *(-20)*	+0.4 *(+20)*	-0.4 *(-20)*	+0.4 *(+20)*
	Prev.maint.activities	-1.2 *(-20)*	+1.2 *(+20)*	-1.3 *(-20)*	+1.3 *(+20)*	-1.4 *(-20)*	+1.4 *(+20)*
	Lifetime	+2.8 *(-12)*	-2.5 *(+12)*	+2.8 *(-12)*	-2.5 *(+12)*	+2.7 *(-12)*	-2.5 *(+12)*

Gulf of Maine shows similar results for the common parameters as the site Golfe de Fos, since the general site characteristics and consequently the common components are not significantly different. The discount rate, for example, has by far the highest effect on the LCOE value. By a decline of 20%, a reduction of the LCOE of more than 13% can be achieved for all FOWT concepts. The parameters offshore substation and turbine cost, as well as turbine availability, energy production and lifetime show similar variation ranges as in Golfe de Fos. However, some differences are observable. For instance, for the Semi-submersible Concrete concept the substructure cost possesses a larger parameter variation and consequently a larger influence on the LCOE than for the other concepts. A 20% variation of the substructure cost can lead to a 4.6% increase or decrease of the LCOE. The Spar concept, on the other hand, is less sensitive to the substructure cost. The maximum variation ranges supposed by the concept designer are -9% and +22%, but cause only a decrease of -0.9% and increase of 2.3%, respectively. The cost of the anchor and mooring system shows only a larger importance for the Spar Concrete concept, which is mainly based on the higher cost of the system for this design and the perception of the concept designer for the uncertainty in the costs. A parameter variation of -20% and +30% is assumed for the mooring cost of the Spar Concrete concept, which results in a LCOE decline of -1.8% and an increase of 2.7%, respectively. The parameters that possess a low influence on the LCOE (below 1%) for this offshore site are corrective maintenance failure rate, inter-array cable and export cable cost.

For the offshore site West of Barra the most predominant parameters are the the discount rate, substructure cost, availability rate and offshore substation cost as well as lifetime and energy production. However, the effect of some parameters has slightly diminished while other parameters have increased their impact on the LCOE compared to the previous discussed offshore sites. For instance, by lowering the turbine costs by 8% a LCOE reduction of around 2.1% to 2.4% is achievable. This is lower compared to the other two offshore sites, where a LCOE reduction of more than 3% was reached. The case of West of Barra shows also a lower share of turbine and substructure cost in reference to the total capital cost since the prices in other components are increased. Furthermore, it can be seen that the Semi-submersible Concrete concept has the larger LCOE variation based on the provided uncertainty values. Regarding the turbine availability, a reduction by half of the rate results in a decline of more than 4% of the LCOE for all three floating wind turbine concepts.

Based on the larger distance to shore at this particular site, the parameters that are related to the distance have a larger influence on the LCOE than in the previous cases. For instance, by reducing the export cable length by 4% or the export cable cost by 17%, a reduction of the LCOE of more than 2% can be reached. The preventive maintenance activities show also a larger influence for this offshore site with a cost reduction potential of up to 1.3%, whereas in the previous sites the influence was 1% or lower. Concerning the inter-array cable cost, no significant influence on the LCOE has been observed based on the defined parameter variations in all three offshore sites. For instance, for the Spar Concrete concept a 20% variation in cable cost would result only in an 0.6% increase or decrease of the LCOE. On the other hand, a 34% shorter inter-array power cable would cause a 1.8% LCOE decline. However, a reduction of the cable length would require further modification of the system design such as the mooring configuration and the wind farm layout. Next, Fig. 7 demonstrates the potential minimum and maximum LCOE limits for the parameters with the defined variation ranges.

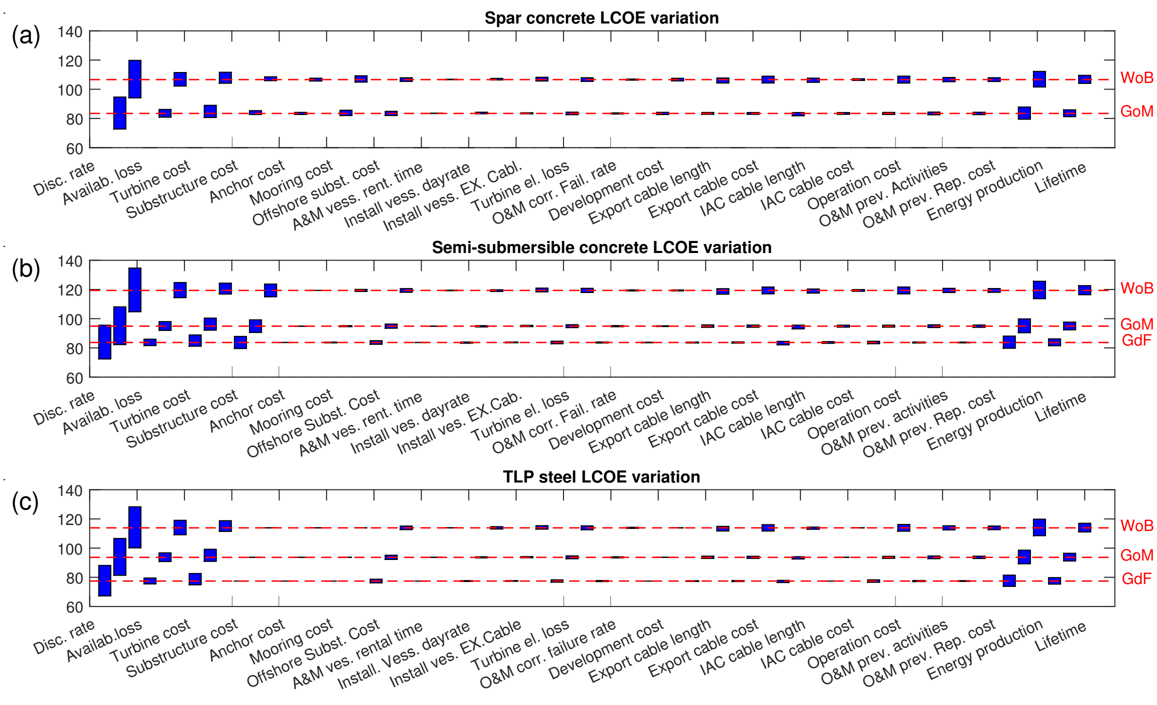


Fig. 7. LCOE variation based on defined parameters for (a) Semi-submersible concrete concept, (b) TLP steel concept and (c) Spar concrete concept

The upper bars in Fig. 7 represent the LCOE variation for the offshore site West of Barra, the central bars represent the Gulf of Maine and the lower bars in line Golfe de Fos. The LCOE values are shown including offshore transmission cost. The figure shows the parameters that have been identified as the most influencing ones on the LCOE and they are presented with their actual LCOE variation potential. For instance, it can be observed that the common parameters such as the turbine and offshore substation cost, as well as the energy related and financial parameters, i.e., availability loss, energy production, lifetime and discount rate, have the largest influence on the LCOE for all three floating wind turbine concepts. From the design dependent parameters the substructure component cost has by far the most influential factor on the LCOE value. However, for the Spar Concrete concept the mooring system is also a significant parameter. Besides that, the figures can serve to identify possible maximum and minimum LCOE values for the defined parameters. The Semi-submersible Concrete concept, for example, could reach based on the provided uncertainty ranges a LCOE as low as 72€/MWh or as high as 135€/MWh depending on the site. The LCOE of the TLP Steel concept, on the other hand, could drop as low as 67€/MWh or reach a maximum value of 128€/MWh. The Spar Concrete concept possesses LCOE values ranging between 72€/MWh and 119€/MWh. However, it should be noted that these values are based only on the variation of one parameter the discount rate and, therefore, are not directly design dependent. In contrast, if the substructure component cost is considered solely one can see that the parameter variation would cause for the Semi-submersible Concrete FOWT concept a minimum LCOE of 72€/MWh and a maximum of 124€/MWh. For the Spar Concrete concept possible LCOE values would be as low as 83€/MWh and as high as 109€/MWh considering only the parameter variation of the substructure component cost. It should also be noted that in this cost estimation no cost reductions based on economies of scale or a large scale employment of the technology are considered.

5. Conclusions

The findings of this study indicate that FOWTs are a high competitive solution and energy can be produced at an equal or lower LCOE compared to bottom-fixed offshore wind or ocean energy technologies. Several key parameters have been identified that have a significant influence on the LCOE and which can be essential for further cost reductions.

For instance, the parameters that most vary the LCOE across all three concepts and offshore sites are manufacturing cost related, such as the cost of the wind turbine, substructure and mooring system. Thus, a cost optimized design involving all components of a FOWT is important and should be considered already in the early design stage. Floating wind specific construction and assembly facilities may also help to reduce costs especially in the manufacturing phase. Steel as well as concrete floating substructures have been studied. The Spar Concrete FOWT has obtained one of the lowest manufacturing cost by combining the advantage of simple manufacturing processes with a low cost concrete material, but the large draft of the Spar restricts the concept to offshore locations with water depths greater than 90m and requires more expensive offshore cranes for mating the turbine with the floating structure. The TLP Steel concept has obtained the lowest LCOE value in this study by having a light structure combined with tense mooring lines. However, the instability of the concept during transportation requires bespoke vessels or buoyancy collars as additional investment to the FOWT. Investigation on TLP designs that are self-stable in the towing process could potentially further reduce the LCOE. The low draft of the Semi-submersible Concrete concept provides a flexible application in both shallow and deep waters. The ability to float independently allows for a simple transportation, which reduces costs along the life cycle. However, the large surface structure results in comparably higher manufacturing costs.

The discount rate plays an important financial parameter since it has the highest influence on the LCOE. The further development of floating wind energy to a commercial technology and the reduction of financial and technological risks can allow to optimize this value. The power cable parameters have also shown a larger influence on the LCOE in the sensitivity analysis. The trend towards bigger turbines requires further development and verification of dynamic cables with higher power capacities and the corresponding electrical connectors. An advantage exists during installation because the power cables can be installed before turbine installation, which allows the performance of parallel installation processes with a decreased installation time. Parameters related to the decommissioning have a smaller influence on the LCOE due to the low share on the total LCC. Nevertheless, the decommissioning of FOWTs has the potential of cost savings in comparison to bottom-fixed offshore wind turbines. The cost savings are in particular true for FOWT concepts that do not require heavy lift vessels and can be towed back to shore by simple tug boats.

Regarding the end of life management, steel floating substructures could benefit from a greater recyclability, whereas concrete substructures may benefit from their longer lifetime and potential reuse. However, further investigation is required on the recyclability and reuse of offshore concrete structures. The offshore substation accounts for a larger portion of the capital cost and thus a variation in the costs has an important influence on the LCOE. Since only one floating substation prototype has been developed so far, further research is needed to study the mutual behavior of the floating substructures and substation in order to reduce technological risks and costs.

The metocean conditions at the different offshore sites possess a significant influence on the LCOE of FOWFs. For instance, West of Barra has increased severe conditions and requires a more robust substructure and higher specialized vessel spreads for installing the anchor and mooring system in reduced weather windows. Installation times could be decreased with higher experience in the sector once the technology reaches a commercial stage and following lessons learned. The maintenance cost, which is based on the failure rate and repair cost, shows also a larger influence for West of Barra. However, since only a few prototypes have been tested for a longer period so far, there is a large uncertainty involved in the assumption of the maintenance cost. A better understanding of the motions and loads acting on the components of FOWTs together with an increased testing period in offshore conditions can help to reduce the uncertainty and optimize costs. West of Barra is the most remote location among the offshore sites studied, which impacts the cost of the export cable and the resulting power losses as well as the transportation cost. Therefore, suitable offshore sites should be selected considering not only the best wind resources, but also the distance to shore and accessibility.

The floating offshore wind technology can be a commercially competitive solution and an excellent component in the energy mix in Europe, but in order to reach the required cost reductions and economies of scale a clear policy commitment and support mechanism are required. Funding of research programs and collaborative innovation programs can support the development of key components of the system that are essential for cost reductions. Moreover, by acknowledging the potential and setting target values for FOWT installations, private investments are attracted that are required for the commercialization of the technology. Besides that, floating wind energy can take advantage of the cost reductions that are achieved in bottom-fixed offshore wind, because many areas of the supply chain are in common use.

Acknowledgements

This work was supported in part by the European Union Horizon 2020 programme under the grant agreement H2020-LCE-2014-1-640741. The first author would like to thank especially the designers of the three floating offshore wind turbine concepts mentioned in this paper for their permission to use respective data and information.

Abbreviations and variables

Abbreviations

CAPEX	Total capital expense
DECEX	Total decommissioning expense
DTU	Technical University of Denmark
FOWAT	Floating offshore wind assessment tool
FOWF	Floating offshore wind farm
FOWT	Floating offshore wind turbine
HVAC	High voltage alternating current
LCC	Life cycle cost
LCOE	Levelized cost of energy
OAT	One-at-a-time sensitivity analysis method
O&M	Operation and maintenance
OPEX	Total operation and maintenance expense
TLP	Tension leg platform
WACC	Weighted average cost of capital

Variables

A_{rotor}	Wind turbine rotor area
C_{Anchor}	Anchor acquisition costs
$C_{A\&M_{instal}}$	Anchor and mooring installation costs
$C_{Anchor\&Moor_{decom}}$	Anchor and mooring decommissioning costs
C_{Cable}	Power cable acquisition costs
$C_{Cable_{decom}}$	Power cables decommissioning costs
C_{Clear}	Area clearance costs
$C_{Commission}$	Commissioning costs
$C_{component}$	Component replacement cost
C_{Corr_maint}	Corrective maintenance costs
C_{Decom}	Decommissioning costs
C_{Dev}	Development costs

C_{Diver}	Diver cost
C_{fuel}	Cost of fuel
$C_{Transport}$	Transportation costs
$C_{IAC\&EX_{instal}}$	Inter-array and export cable installation costs
C_{Instal}	Installation costs
C_{Manuf}	Manufacturing and purchasing costs
$C_{Mooring}$	Mooring system acquisition costs
$C_{O\&M}$	Operation and maintenance costs
$C_{Operation}$	Operation expenses
C_p	Power coefficient
C_{Prev_maint}	Preventive maintenance costs
$C_{Substation}$	Substation acquisition costs
$C_{Substation_{decom}}$	Substations decommissioning costs
$C_{Subst_{instal}}$	On- and offshore substation installation costs
$C_{Substruct}$	Substructure manufacturing costs
$C_{Treatment}$	Final treatment costs
C_{Turb}	Turbine acquisition costs
$C_{Turb\&FS_{instal}}$	Turbine and substructure installation costs
$C_{Turb\&FS_{decom}}$	Turbine and substructure decommissioning costs
C_{vessel}	Day rate vessel for preventive maintenance
$C_{vessel\&cranes}$	Day rate vessel and cranes for corrective maintenance
C_{wear}	Cost of wear parts
D	Debt
$E_{available}$	Energy available
E_{el}	Energy provided
E_t	Energy generated
E	Equity
F_{rate}	Failure rate
$H_{metocean}$	Occurrence probability of metocean condition
I_{cable}	Power cable current
K	availability
k_D	Cost of debt
k_E	Cost of equity
l_{cable}	Power cable length
L_{fuel}	Fuel consumption
L_t	Energy losses
$N_{activities}$	Number of maintenance activities
n	Year of lifetime end
ρ_a	Air density

$P_{metocean}$	Power generation dependent on metocean conditions
P_{cable}	Power cable loss
r	Discount rate
R_{cable}	Power cable resistance
T_D	Downtime
T_N	Nominal time
t	Year
t_{vessel}	Vessel rental time for preventive maintenance
$t_{vessel\&cranes}$	Vessel rental time for corrective maintenance
v_{wind}	Wind speed at hub height

References

[1] GWEC . Global wind 2017 report. Brussels; 2017.

[2] Atcheson M, Garrad A. Looking back. In: Cruz J, Atcheson M, editors. Floating Offshore Wind Energy: The Next Generation of Wind Energy. Springer International Publishing Switzerland; 2016, p. 1–20.

[3] Carbon Trust . Floating offshore wind: market and technology review. London; 2015.

[4] WindEurope . Floating offshore wind vision statement. London; 2017.

[5] IRENA . Renewable energy technologies: Cost analysis series wind power. Abu Dhabi; 2012.

[6] Myhr A, Bjerkseter C, Ågotnes A, Nygaard TA. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Renewable Energy 2014;66:714–28.

[7] Kausche M, Adam F, Dahlhaus F, Großmann J. Floating offshore wind-economic and ecological challenges of a TLP solution. Renewable Energy 2018;126:270–80.

[8] Laura CS, Vicente DC. Life-cycle cost analysis of floating offshore wind farms. Renewable Energy 2014;66:41–8.

[9] Castro-Santos L, Diaz-Casas V. Economic influence of location in floating offshore wind farms. Ocean Engineering 2015;107:13–22.

[10] Ebenhoch R, Matha D, Marathe S, Muñoz PC, Molins C. Comparative levelized cost of energy analysis. Energy Procedia 2015;80:108–22.

[11] WindEurope . Deep water the next step for offshore wind energy. Brussels; 2013.

[12] Ebenhoch R. Comparative levelized cost of energy analysis for a floating offshore wind turbine concept. Master's thesis; Student research paper at Stuttgart Wind Energy (SWE); Stuttgart (Germany); 2014.

[13] LIFES50plus . Innovative floating offshore wind energy. http://lifes50plus.eu; 2017 [accessed 01 June 2017].

[14] Benveniste G, Lerch M, de Prada Gil M. Lifes50plus deliverable 2.2: LCOE tool description, technical and environmental impact evaluation procedure. Barcelona; 2016.

[15] Crown Estate . A guide to an offshore wind farm. London; 2010.

[16] Bjerkseter C, Ågotnes A. Levelised cost of energy for offshore floating wind turbine concepts. Master's thesis; Norwegian University of Life Sciences; 2013.

[17] Kaiser MJ, Snyder BF. Offshore Wind Energy Cost Modeling: Installation and Decommissioning. Springer-Verlag London; 2012.

[18] Castro-Santos L, Filgueira-Vizoso A, Carral-Couce L, Formoso JÁF. Economic feasibility of floating offshore wind farms. Energy 2016;112:868–82.

[19] Brons-Illing C. Analysis of operation and maintenance strategies for floating offshore wind farms. mathesis; University of Stavanger; 2015.

[20] Breyer C. Economics of hybrid photovoltaic power plants. Ph.D. thesis; University of Kassel; 2012.

[21] Castro Santos L. Methodology related to the development of the economic evaluation of floating offshore wind farms in terms of the analysis of the cost of their life-cycle phases. Ph.D. thesis; University of A Corua; 2013.

[22] Fernando DB, Hernán dB, Ricardo JM. Wind Turbine Control Systems: Principles, Modelling and Gain Scheduling Design. Springer; 2006.

[23] Jensen NO. A note on wind generator interaction. Risø National Laboratory Roskilde 1983;.

[24] Bredmose H. Generic layout for the 3 sites with calculated production loss and effective turbulence intensity from wake effects. Lyngby; 2016.

[25] GL Garrad Hassan . A guide to uk offshore wind operations and maintenance. hassan2013guide; 2013.

[26] Hau E, von Renouard H. Wind turbines: fundamentals, technologies, application, economics. Springer; 2003.

[27] Sarajcev I, Majstrovic M, Medic I. Calculation of losses in electric power cables as the base for cable temperature analysis. WIT Transactions on Engineering Sciences 2000;27.

[28] Fassò A, Perri PF. Sensitivity analysis. In: El-Shaaraw A, Piegorsch W, editors. Encyclopedia of environmetrics; vol. 4. Wiley; 2002, p. 1968–82.

[29] Hamby D. A review of techniques for parameter sensitivity analysis of environmental models. Environmental monitoring and assessment 1994;32(2):135–54.

[30] Borgonovo E. Sensitivity Analysis: An Introduction for the Management Scientist. Springer; 2017.

[31] Dr. techn. olav Olsen, OO-star Wind Floater. http://www.olavolsen.no/en/node/149; 2017 [accessed 05 September 2017].

[32] Iberdrola Engineering & Construction, TLPWind. https://www.iberdrolaingenieria.com/ibding/pagina?id=119&itemMenu=50&locale=en; 2017 [accessed 10 September 2017].

[33] Windcrete . Concrete floating platform for wind turbines. http://www.windcrete.com; 2017 [accessed 14 September 2017].

[34] Bak C, Zahle F, Bitsche R, Kim T, Yde A, Henriksen LC, et al. The DTU 10-MW reference wind turbine. Fredericia; 2013.

[35] Gonzalez S, Diaz-Casas V. Present and future of floating offshore wind. In: Floating offshore wind farms. Springer; 2016,.

[36] Dr. Techn. Olav Olsen . Oo-star wind floater- an innovative and robust semi-submersible for offshore floating wind. Seoul; 2017.

[37] IRENA . Floating foundations: A game changer for offshore wind power. Abu Dhabi; 2016.

[38] Henderson A, Collu M, Masciola M. Overview of floating offshore wind technologies. In: Cruz J, Atcheson M, editors. Floating Offshore Wind Energy: The Next Generation of Wind Energy. Springer International Publishing Switzerland; 2016, p. 87–132.

[39] Mller K, Matha D, Karch Michael andTiedemann S, Proskovics R. Lifes50plus deliverable 7.5: Guidance on platform and mooring line selection, installation and marine operations. Stuttgart; 2016.

[40] Castro Santos L, Diaz-Casas V. Life-cycle cost of a floating offshore wind farm. In: Castro Santos L, Diaz Casas V, editors. Floating offshore wind farms. Springer; 2016, p. 23–38.

[41] Campos A, Molins C, Gironella X, Trubat P. Spar concrete monolithic design for offshore wind turbines. In: Proceedings of the Institution of Civil Engineers-Maritime Engineering. 2016, p. 49–63.

[42] Mller K, Faerron-Guzmn R, Manjock A, Borg M. Lifes50plus deliverable d.7.7: Identification of critical environmental conditions and design load cases. Stuttgart; 2018.

[43] Gomez P, Sanchez G, Llana A, Gonzales G, Berque J, Aguirre G. Lifes50plus deliverable: 1.1 oceanographic and meteorological conditions for the design. Madrid; 2015.

[44] Carbon Trust . Floating wind joint industry project - phase I summary report. London; 2018.

[45] Carbon Trust . Accelerating marine energy: The potential for cost reductioninsights from the carbon trust marine energy accelerator. London; 2011.

[46] Duan F. Wind energy cost analysis coe for offshore wind and lcoe financial modeling. Master's thesis; Helsinki Metropolia University of Applied Sciences; 2017.

[47] UK Department for Business, Energy & Industrial Strategy, Contracts for Difference Results. https://www.gov.uk/government/publications/contracts-for-difference-cfd-second- allocation-round-results; 2017 [accessed 12 September 2017].

[48] Astariz S, Vazquez A, Iglesias G. Evaluation and comparison of the levelized cost of tidal, wave, and offshore wind energy. Journal of Renewable and Sustainable Energy 2015;7(5):053112.

[49] Stoutenburg ED, Jenkins N, Jacobson MZ. Power output variations of co-located offshore wind turbines and wave energy converters in california. Renewable Energy 2010;35(12):2781–91.

[50] Benveniste G, Lerch M, de Prada Gil M. Lifes50plus deliverable 7.6: Framework for LCOE, uncertainty and risk considerations during design. Barcelona; 2017.

[51] ORE Catapult . Offshore transmission benchmarking and cost monitoring. Blyth; 2016.